ECONOMIC DAMAGES TO HOUSEHOLD ITEMS

FROM WATER SUPPLY USE IN

THE UNITED STATES

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ABSTRACT

Household appliances and personal items in contact with water supply are subject to physical damages from chemical and other constituents of the water. This study translates these damages into economic losses for a typical household. Then it aggregates these losses at the national and individual state levels. To do so requires several stages of analysis. First, the types of physical damages expected and associated water quality determinants are identified. The physical effects are next translated into economic losses. Second, damage functions are formulated to predict likely impacts of water quality changes on each household unit affected. Third, a computer program based on these functions is designed to estimate. total damages per typical household and to aggregate them over selected regions. Finally, the program is applied to state-by-state data on water supply sources and socioeconomic descriptors. Total damages to U.S. residents in 1970 are estimated in the range, $0.65 to $3.45 billion; with a mean of $1.75 billion. The mean translates into $8.60 per person. States contributing most to total damages are California ($230 million) and Illinois ($164 million). On a per capita basis, Arizona ($22.53) and New Mexico ($18.58) rank highest, whereas South Carolina ($1.15) and Oregon ($1.73) are at the other end of the spectrum. When per capita damages are compared by source of water supply, those from private wells are worst at an average of $12.34, treated ground water next at $11.20, and treated surface water

sources at only $5.83.

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SECTION I

CONCLUSIONS

Some of the key conclusions drawn from this household damage study are summarized in the following items. Additional insights may be obtained by surveying the list of references in Section XI.

1. In the United States, total 1970 damages to household items from water supply use were in the range, \$0.65 - \$3.45 billion, with a mean of \$1.75 billion.
2. On a per capita basis, the mean damage estimate is \$8.60 in 1970.
3. Those states with the highest mean estimate of damages include California at \$230 million and Illinois at \$164 million.
4. Per capita damages are highest for Arizona, \$22.53, and New Mexico, \$18.58.
5. Per capita damages differ significantly with respect to the source of water supply. Those consumers using surface water supplied by public systems incur damages averaging \$5.83, compared with \$12.34 for private well owners.
6. The most significant water quality parameters affecting household expenditures include hardness, total dissolved solids, chlorides and sulfates, and acidity.
7. Economic impacts of water supply use on household items are measurable in terms of increased investment and operating costs.

8. Damage functions are formulated to estimate the impact of water quality on the service life and operating levels of nearly twenty household items.
9. The household items most vulnerable to deteriorating effects of water quality parameters include piping, water heaters and other appliances, washable fabrics, water utility systems, and soap purchases.

SECTION II

RECOMMENDATIONS

Several recommendations on treatment strategies and research priorities are listed below as implied by this household damage study.

1. Economic tradeoffs of controlling water quality parameters, such as hardness and total dissolved solids, in a central plant vs. residential homes should be analyzed on a regional basis.
2. Household damage functions from water supply use should be derived from local conditions. Although communities with water supply containing excessive amounts of certain constituents have been observed to some degree, other communities within “recommended standards" should not be ignored. The latter group must also contend with significant damages in the residential sector.
3. More information about water quality data and water use patterns should be collected on private water distribution systems.
4. More research should focus on household damages incurred by the use of water with very low concentrations of constituents. Synergistic effects of constituents at these quality levels should also be explored.

SECTION III

INTRODUCTION

The primary objective of water supply control is to protect the public health and welfare in the use and enjoyment of water resources. The health aspect of water quality criteria has been under investigation for many years, while aesthetic properties have also influenced the development of water treatment technologies. Obviously, the protection of human health and aesthetic factors are of paramount concern (e.g., CDC, 1971; J. Lackner, 1973), but other welfare aspects also relate to drinking water characteristics. Beyond its direct consumption, water is used in household activities, such as dish washing. Household appliances and plumbing, which come into daily contact with water supply, are subject to abrasive, corrosive, and other damaging effects of certain constituents in water.

This study focuses on household damages while recognizing the importance of other welfare aspects. Economic impacts of water supply use affect household costs in both the long and the short run. The service life of household items increases from contact with improved water quality. In addition, daily expenditures for soap and detergents as well as operating costs of appliance usage can decline. Unfortunately, these impacts are usually neglected, even in comprehensive water quality damage studies. A major study of estuarine pollution problems (FWPCA, 1966), for example, concludes that the benefits of more stringent control are probably not large given the existence of treatment plants which are necessary in any case.

The misconception underlying this rationale is that treatment supposedly removes all objectionable pollutants prior to household water distribution. Such is not the case, however, in normal treatment plants. Total dissolved solids (TDS) and hardness are among those elements not treated extensively in public systems. It is well documented that these and other constituents can inflict severe damages on households. Although there are suggested limits of concentration for these parameters, standards have not yet been promulgated. According to some economists, "... little rigorous evidence is available on which to base a limiting standard for drinking water with respect to total dissolved solids" (Kneese and Bower, 1968).

This study demonstrates that the economic damages from domestic water supply use are substantial and should thus be considered in defining water quality standards. Empirical evidence is reviewed from the literature and cast into a model framework to predict total damages in a specific region. The first section of the paper identifies major pollutants and their physical impacts on household items. The next section presents a method of translating these damages into economic equivalents. Following this, a predictive model is derived, after which total damage estimates.are calculated by state. These values are based on complete removal of objectionable wastes. Moreover, they include all residents served by either public or private water distribution systems. Finally, partial damages are estimated in meeting recommended standards of water supply rather than complete removal.

SECTION IV

PHYSICAL IMPAIRMENT OF HOUSEHOLD UNITS

Water supply should be of sufficient quality to be safe for direct consumption and to provide for its normal uses in household activities. Most contaminants in water supply are captured and removed at the water treatment plant. But not all constituents are removed, the most notable exceptions including the components, hardness and total dissolved solids (TDS). Plants seldom reduce hardness below 85-100 ppm (Larson, 1963). Conventional water treatment processes do not readily or economically remove a significant portion of the mineral content.

Most public water supplies are within Federal recommendations limiting total dissolved solids concentration to 500 ppm (USPHS, 1963). Only 2 percent of water distributed through these systems, serving 160 million Americans, does not meet this criterion (Patterson and Banker, 1969). Yet compliance with this criterion does not imply that economic damages from water use are avoided. Corrosion and accelerated depreciation of household appurtenances have been observed at low concentrations of the water constituents. Moreover, it is generally less costly to improve water at the plant than in the homes. Sonncn (1973) demonstrated that household and industrial damages from mineralized water supplies in a California community exceeded the cost of water and waste treatment by conventional processes. Howson (1962) reported that water softening in some Wisconsin towns was ten times more expensive than municipal treatment.

The costs of water supply thus extend beyond municipal treatment. and distribution to include the customer's use of water. Water quality-related consumer costs are delineated into two basic categories; as defined by the Santa Ana Watershed Planning Agency (Leeds, Hill, and Jewett, Inc., 1969). Under direct control by the user is the cost of specialized treatment for the removal of objectionable water constituents. The other cost measures the penalty attributed to the use of degraded water supply. According to the Planning Agency, the latter cost occurs "as a result of using water of particular quality. Such items as Increased use of soap, scaling of pipes, and rapid deterioration of plumbing fixtures and water-using appliances are examples of the penalties incurred by the domestic user ... . " These two categories are interdependent since specialized treatment reduces penalty costs. Ideally the household degree of treatment should be optimized by setting the marginal increase of treatment cost equal to the incremental decrease of penalty costs at the desired quality of water intake.*

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*For some residents, the optimal solution must be constrained by other preferences of drinking water. Although there may be significant physical damages from certain water quality characteristics, many consumers are willing to undergo these costs because of a taste preference for this water. Should these

Damaging effects of water supply result primarily from corrosion, encrustation, and despoiling of household items that come into frequent contact with poor quality water. Affected items in the home include piping systems, plumbing fixtures, water heaters and other appliances, washable clothing and fabrics, dishes and miscellaneous goods. Specialized water treatment, i.e., water softening, extra demand for soap and detergents, and the purchase of bottled water represent additional costs. Degraded water can inhibit houseplant growth and necessitate more frequent lawn irrigation. In addition, damages are incurred by water utility systems and customer facilities. A breakdown of these items includes water tanks, meters, pumps, and municipal water distribution systems.

Water quality parameters having the greatest economic impact on household use are (Leeds, Hill and Jewett, Inc., 1970; Metcalf & Eddy, 1972) :

(1) Total dissolved solids (TDS). The useful service life of household plumbing fixtures and appliances is sensitive to the mineral content of water (Black and Veatch, 1967).

(cont'd)

constituents be removed, the water would then become objectionable. Senate Drinking Water Bill 433 in early 1973 recognized these preferences by recommending local options for secondary (aesthetic as opposed to health oriented) drinking water standards.

Corrosion of metallic surfaces and precipitation of scale are the most apparent damages linked to the presence of minerals including calcium, magnesium, iron, manganese, sodium, potassium, sulfate, and chloride. Iron and manganese, in particular, cause staining and can even clog piping and fixtures. The demand for bottled water and extensive lawn watering are strongly related to the level of mineralization. There are no legal restrictions on the TDS content of water supplies. The U.S. Public Health Service recommends that treated water not exceed 500 ppm of TDS, but this criterion is based on potability rather than physical damages in the household sector. Indeed, there are no commonly accepted criteria for any parameters that affect consumer costs.

(2) Hardness. Water softening, scale deposits in water heaters, and purchases of soap and detergents are likely to increase with the use of hard water, whose primary constituents are calcium and magnesium compounds. Although high degrees of hardness are detrimental to water systems, low concentrations can be beneficial since the resultant scaling reduces corrosion by applying a "uniform deposit that completely covers the metallic surfaces" (Black and Veatch, 1967). The U.S. Geological Survey (1964) classifies water hardness in

terms of the concentration of calcium carbonates:

0 - 60 ppm	soft
60 - 120	moderately soft
120 - 180	hard
180 +	very hard.

Generally, household users become irritated with hardness exceeding 150 ppm while that above 300 ppm is considered excessive (FWPCA, 1968).*

(3) Chlorides and sulfates. Corrosion and scaling are caused by chemical action involving these anions. Alone they do not cause corrosion, but they lower the pH of water and thus hasten deterioration. Chlorides are statistically shown (Patterson and Banker, 1968) to decrease the service period of water heaters, while sulfates in conjunction with magnesium ions, due to

*The effects of hardness on human health are not addressed here, although they are frequently debated in the literature. For example, many researchers found strong associations between heart ailments and water softness (e.g., Shroeder, 1960; Morris, et al, 1961), while others claimed that these results were spurious since all causal factors were not considered (Dingle, et al, 1964).

their laxative effect, promote bottled water consumption (Metcalf & Eddy, 1972).

(4) Acidity. Reduced service life of customer facilities may be expected from contact with highly acidic water. Acidity is corrosive at levels below 5.0. But it is not a factor of concern in most treated water, where the pH level falls between 6.5 and 8.5 (McKee and Wolf, 1971).

Other important water quality parameters include sodium, potassium, phosphates, silicates, and dissolved gases. But the above four categories are most often recognized as damaging to household items.

In estimating household damages in economic terms, this study proposes to use only two water quality measures, total dissolved solids and hardness, for several reasons. First, most empirical results reported in the literature are based on these parameters. Second, there is ample data on these descriptors of water supply throughout the United States. It must be recognized, however, that these agents are not solely responsible for gross damages. For example, without an adequate supply of dissolved oxygen in water, corrosion is seriously retarded. And warmer water tends to hasten corrosive or scaling actions. Synergistic effects of water quality conditions must therefore be recognized, hut for the sake of computational simplicity, the most fundamental parameters are used in estimating damages.

SECTION V

ECONOMIC COSTS TO THE CONSUMER

The literature contains numerous estimates, by household item, of the economic impacts of degraded water supply. Some of these results are useful in calculating state and national benefits of water pollution control. Cost impacts are generally separated into investment outlays for the replacement or disposal of damaged household units and daily operation and repair expenses. The most comprehensive estimate of consumer costs is reported by Black and Veatch (1967). Annualized capital costs (discounted at 6 percent interest) and annual operating costs are estimated for a number of household or household-related units, ranging from water piping and clothing to water meters and distribution storage systems. Even expenses for soap, bottled water, and lawn over-irrigation are itemized. Curves are plotted to predict the average useful life of facilities over various qualities of water supply.

The Black and Veatch report restricts its water quality data base to total dissolved solids. Damages primarily attributed to hardness are omitted from discussion, although later estimates in this study show that hardness has greater economic effects than TDS. Moreover, total damage estimates are provided for only two extreme water quality cases with TDS concentrations of 250 and 1,750 ppm. Intermediate cases are not easily interpreted from these results because some of the damage functions per household unit are nonlinear while others are linear over the water quality range. The extreme case estimates are based on interviews in thirty-eight western municipalities, most of which are quite small. To extrapolate these results to other regions would require adjustments for household expenditures and water consumption. Yet the report distinguishes average vs. modern urban residential costs of using the same quality water. For these resident groups, the difference in per capita damages for the extreme water quality cases is $46.70 and $60.55, respectively.* But these estimates include bottled water and lawn over-irrigation costs, which are specific to an area and to a small percentage of all families. Without these items the respective damages are lowered to $17.22 and $28.97.

Two other estimates (Hamner, 1964; AWA, 1961), both reported by the American Water Works Association, relate average TDS effects on household facilities only (excluding soap, fabrics, bottled water, irrigation, and water utility systems). These figures are $12.95 and $12.63-$18.96, respectively, which compare favorably with a

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*The urban residential family consumes, on the average, 130,000 gallons of water per year compared to 100,000 gallons in the typical home. The per capita figures pertain to a typical household with 3.8 persons.

corresponding value of $13.13 by Black and Veatch. Their estimates of bottled water purchases, however, are somewhat lower than Black and Veatch figures by roughly 20 percent. Patterson and Ranker (1968) use data in the Black and Veatch report to estimate effects of TDS on appliances and plumbing facilities. Their conclusions are thus similar to the latter study, although they contend that due to the subjective nature of some estimates, "the results . . . should be looked upon as an initial investigation, certainly subject to more complete survey investigation and analysis."

Leeds, Hill and Jewett, Inc. (1969) estimate specialized treatment and penalty costs associated with household facilities, using both TDS and hardness parameters. Damages are assumed directly proportional to the water quality level. For the Santa Ana River Basin, per capita damages for 1970 are assessed at $18.85, with hardness contributing about two-thirds of the total. This figure is probably higher than the national average since water quality is relatively low and household expenditures high in this area.

Metcalf and Eddy (1972) conducted on-site interviews for damage estimates mainly from Southwestern communities with supplemental data from industry. Unlike most other studies that simply aggregate damages over each household unit, this report statistically verifies the significance of water quality effects. The most important relations are found to be bottled water purchases vs, TDS, softening costs and soap demand vs. hardness, and frequency of water heater replacement vs. chlorides. No significant effects of water quality are identified with lawn watering, clothing expenses, and plumbing repairs. Other studies, on the other hand, reach opposite conclusions. Certain minerals are found to have detrimental effects on dishes, glassware, and appliances (Syracuse Chine Corp., 1971; Anchor Hocking Glass Corp., 1971; Frigidaire Div., 1971). Dissolved solids can stain, discolor, and shorten fabric life (Loeb, 1963; Olson, 1939; Hein, 1971); Aultman, 1958). Metcalf and Eddy derive two exponential curves for total household costs vs. hardness with and without softening devices. For excessive water hardness of 400 ppm, per capita damages are $22.33. A serious problem with this study is that it derives total household costs only in terms of hardness levels. The interviews are conducted primarily with housewives, most of whom lack awareness of damaging minerals other than hardness, since the latter affects soap costs. As a result, cost estimates are biased in favor of hardness and omit other important water quality factors (Bovet, 1972).

An Orange County Study (1972) estimates the average per capita economic damage resulting from use of Colorado River water. Household items include water softeners, bottled water, water heaters, plumbing, water-using appliances, and swimming pools. Linear damage relations are assumed. Annual costs from both dissolved solids and hardness are quite high at $39.84, since water quality (average TDS load of 746 ppm; hardness, 349 ppm) of the riverwater supplied to households is quite poor.

Several studies examine damages for specific household items. Every 100 ppm rise in water hardness increases soap consumption. For example, the annual per capita cost of cleaning products varies considerably by study, i.e., $1.55 in an Illinois study (DeBoer and Larson, 1961), $2.52 in a Purdue University study (Aultman, 1958), $5.85 in a Southern California study (Metropolitan Water District, 1970), $8.21 for upper middle income residents in an Orange County survey (1970), and $3.32 for all respondents in this survey.* In a report on the Ohio River Valley (Bramer, 1960), hardness-related costs of soap are based on the Purdue University data. However, when total basin costs are derived, only customers using publicly treated surface water supplies are counted. Other residents on private wells and ground water are excluded since these sources, as the author contends, are not "primarily subject to the effects of pollution." This assumption is questionable since ground water is subject to (man-made) contamination from salts and toxic materials from surfaces and deep wells or through diffusion of soluble compounds from septic tank systems (Todd, 1970).

*These figures are inflated by suitable price indices to base year 1970. The final estimate is based on a straight-line fitted through all data points in the Orange County survey.

Williams (1968) determined home water softening costs at $26.64 per person in Southern California. In a related study, the per capita cost of cleaning agents due to all water constituents is estimated in the range, $12.63-$15.79, for most American cities (AWWA, 1961). Another measure of benefit estimates is based on the willingness-to-pay concept. Orange County residents were asked what additional expenses they would accept for top quality water (Orange County Water District, 1972). Average yearly payments were $5.68 and $8.84 for water with respective TDS loads below and above 600 ppm.

SECTION VI

METHODOLOGY FOR ESTIMATING BENEFITS

The sequence of calculations for marginal benefits of water quality improvement is outlined in Figs. 1 and 2. In the first diagram, damages are calculated for each household item. These costs are partitioned into (1) investment and (2) operation. The former cost involves annualizing total capital cost over its period of usefulness. The reduced service life of unit i, resulting from contact with low vs. high quality water, is estimated by damage function $F_i(\cdot\cdot)$. The appropriate water quality index-TDS or hardness level--is an independent variable in this function. A standard capital recovery factor is defined in terms of the service life n and discount rate r, as follows:

$$\alpha(r, n) = \frac{r^n(1+r)^n}{(1+r)^n - 1} . \tag{1}$$

This value, multiplied times the original value of the item, effectively amortizes the original cost into n equal yearly payments at interest r. The annualized cost decreases with improving water quality. This change represents the damage estimate for equipment corrosion or depreciation.

The other cost element arises from greater operation and maintenance of household items. This annual cost is calculated by the damage function $G_i(\cdot\cdot)$. After total costs are estimated for the two

Damage Impact	Description of unit u	Water Quality Level Actual (W_o)	Improved (W_i)
Investment	Useful service life	$n_{uo} = F_u\ (W_o)$	$n_{ui} = F_u\ (W_i)$
	Capital recovery factor	$\alpha(r, n_{uo})$	$\alpha(r, n_{ui})$
	Base year value	V_u	V_u
	Annualized value	$\alpha(r, n_{uo}) \cdot V_u$	$\alpha(r, n_{ui}) \cdot V_u$
	Incremental damage	$D_u^{(1)} = [\alpha(r, n_{ui}) - \alpha(r, n_{uo})] \cdot V_u$	
Operation	Base year cost	$G_u\ (W_o)$	$G_u\ (W_i)$
	Incremental damage	$D_u^{(2)} = G_u\ (W_i) - G_u\ (W_o)$	
Total Unit	Incremental damage	$D_u = D_u^{(1)} + D_u^{(2)}$	
Total Household	Incremental damage	$D_u = \sum_u D_u$	

*Note: Water supply source, j, is implicit in these symbols i.e., $D \simeq D_j$.

Fig. 1. SCHEMATIC DIAGRAM OF WATER QUALITY DAMAGE CALCULATIONS FOR EACH HOUSEHOLD UNIT.

Land Area	Description of Region	Water Supply Source		
		Public: Surface	Public: Ground	Private: Well
State	Household Damages			
	Typical	D_1	D_2	D_3
	Adjusted for State	D_{1s}	D_{2s}	D_{3s}
	Number of Households	f_{1s}	f_{2s}	f_{3s}
	Total Damages by Source	$f_{1s}D_{1s}$	$f_{2s}D_{2s}$	$f_{3s}D_{3s}$
	Total Damages		$T_s = \sum_j f_{js}D_{js}$	
	Total Population		g_s	
	Per Capita Damages		$P_s = T_s/g_s$	
Nation	Total Damages by Source	$\sum_s f_{1s}D_{1s}$	$\sum_s f_{2s}D_{2s}$	$\sum_s f_{3s}D_{3s}$
	Total Damages		$T = \sum_s T_s$	
	Total Population		$g = \sum_s g_s$	
	Per Capita Damages		$P = T/g$	

Fig. 2. AGGREGATION SCHEME FOR REGIONAL WATER QUALITY BENEFIT CALCULATIONS.

water quality conditions, they are subtracted to yield incremental damages.

Unit damage functions and input data for these calculations are extracted from the literature. For most units, damage curves have been formulated from manufacturers' data and personal interviews. Otherwise, curves must be fitted through available data points. If only two (extreme water quality) observations are available, a linear segment is drawn through these points. In those cases where several data sources are available, averages are taken. There are also household items owned by a portion of all households, i.e., water softeners. This portion is assumed to be linearly related to the level of water quality (Orange County Water District, 1972). As a result, the average damage is a product of item cost and percent ownership, both functions of water quality. Price indices (Census, 1971) of household items are multiplied times original cost to adjust damages to base year 1970.

Table 1 presents a list of household units included in this study. Corresponding (uninflated) damage functions are formulated for capital and operating costs in a typical residence. Functional dependence on specific water quality conditions is also identified. (Note that soap and detergent costs are apportioned between TDS and hardness.) Each function is assumed valid over the observed range of water quality, although some studies caution the use of extrapolated results.* Not all household units are considered in estimating

Table 1
TYPICAL DAMAGE FUNCTIONS FOR HOUSEHOLD UNITS

UNIT	INVESTMENT/FAMILY * ORIGINAL COST ($)	LIFE SPAN (YR)	OPERATION AND MAINTENANCE * ($/YR)	WATER QUALITY VARIABLE (W) TDS	HARDNESS
Bottled Water	0	0	$\exp(-3.7)\cdot W^{.8}$	●	
Cooking Utensils	20	$10.2 - 7.0^{-4}W$	0	●	
Faucets	165	$11.5 - 2.7^{-4}W$	$7.0^{-4}W + 1.6$	●	
Garbage Grinder	8	$5.0 + 1.6\cdot\exp(-1.2^{-3}W)$	$5.0^{-4}W + 1.1^{-1}$	●	
Sewage Facilities	90	$30.8 - 3.3^{-3}W$	$2.3^{-4}W + 3.4$	●	
Soap & Detergents (1)	0	0	$2.7^{-3}W + 11.7$	●	
Soap & Detergents (2)**	0	0	$1.6^{-1}W\cdot(1-X) + 11.7,$ $X = 7.0^{-4}W$		●
Toilet Facilities	20	$2.0 + 2.4\cdot\exp(-1.5^{-3}W)$	$1.6^{-3}W + 6.1^{-1}$	●	
Washable Fabrics	1,080	$4.6 - 1.3^{-4}W$	0	●	
Washing Appliances	120	$5.0 + 1.8\cdot\exp(-7.9^{-4}W)$	$1.0^{-3}W + 3.3$	●	
Wastewater Piping	450	$10.0 + 3.8\cdot\exp(-6.4^{-4}W)$	$7.0^{-4}W + 1.6$	●	
Water Heater	110	$5.0 + 2.4\cdot\exp(-1.4^{-3}W)$	$1.3^{-3}W + 16.8$	●	

Table 1 (continued).

UNIT	INVESTMENT/FAMILY * ORIGINAL COST ($)	INVESTMENT/FAMILY * LIFE SPAN (YR)	OPERATION AND MAINTENANCE * ($/YR)	WATER QUALITY VARIABLE (W) TDS	WATER QUALITY VARIABLE (W) HARDNESS
Water Piping	250	$12.0 + 3.4 \cdot \exp(-1.8^{-3}W)$	$1.1^{-3}W + 2.0$	●	
Water Softeners **	$2.1^{-1}W$	12.0	$1.1^{-4}W^2$		●
Water Utility Systems					
Distribution	450	$60.0 + 3.9 \cdot \exp(-9.1^{-4}W)$	$1.2^{-3}W + 3.2$	●	
Production	120	$30.8 - 3.3^{-3}W$	$3.2^{-4}W + 4.5$	●	
Service Lines	100	$46.7 - 6.7^{-3}W$	0	●	
Storage	60	$50.8 - 3.3^{-3}W$	$6.3^{-4}W + 3.4^{-1}$	●	
Water Meter	40	$30.5 - 2.0^{-3}W$	$2.3^{-4}W + 5.9^{-1}$	●	

* Any number of the form, $a.b^{-n}$, is an abbreviation of the scientific notation, $a.b \times 10^{-n}$.

** Damages for this unit are adjusted by the proportion of households owning water softeners.

damages. Only those with adequate documentation and proven dependence on water quality are summarized. Other likely items include ornamental shrubbery, swimming pools, home garden crops, and extra fertilizer demand.

After typical household damages are derived, state and national totals follow according to Figure 2. Each unit estimate is first adjusted to reflect state differences in housing expenditures. This adjustment is based on findings (Orange County Water District, 1972) of a strong correlation between damage levels and home value or rent payment. The factor used to reflect this standard of living adjustment is the ratio of average family income by state over the U.S. mean (Census, 1972).

Levels of drinking water quality for the largest U.S. cities (Durfor and Becker, 1965) are closely related to the quality of the

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*In the communities surveyed by Metcalf and Eddy (1972), for example, TDS always exceeded 31 ppm in water supplies, so that any damage estimate based on purer water is subject to greater uncertainty than interpolated results. Sonnen (1973) and others assume that damages are negligible below certain concentrations of minerals, i.e., 100 ppm for hardness, since no observations were surveyed in this range. Another survey (Aultman, 1958) refutes this assumption.

original water supply. Thus damages in each residence depend on the supply source, which is usually distinguished as publicly treated surface water, publicly treated ground water, or well water and other private sources. To estimate the number of households served by each supply source requires the integration of several data sets. The Environmental. Protection Agency (Division of Water Hygiene, 1971) summarizes the percent of each state's population served in 1970 by public water supply systems. The remaining (unreported) population receives water from private systems. Of the proportion on public supply, a USGS report (Murray and Peeves, 1972) divides it by state into population served by surface, ground water, or combination thereof. For purposes of this study the "combination" group (which is relatively small) is partitioned among pure surface and ground water users according to their relative magnitudes. These estimates thus give a breakdown of state customers served by the three major water sources. The number of households on each source equals the percent served by source times total number of families (used as a proxy for households).

This analysis concerns itself not so much with the origin of damages as with the total use of water. Yet the distinction among household damages by supply source is important for several reasons. First, pollution of surface sources is more often identified with man-made activities than ground water contamination (Bramer, 1960). Water quality standards are generally designed to control anthropogenic wastes in surface water bodies. Second, water quality levels differ significantly by source. According to chemical analyses of raw water from large public supplies in the United States (U.S. Geological Survey, 1954), average hardness as $CaCO_3$ (weighted by population on each supply source) is 96 ppm from surface supplies but 200 ppm from ground supplies. If the water is treated publicly, these figures are reduced to 82 and 162 ppm. Total dissolved solids (measured as residue at 180 deg. F.) levels also vary considerably and are notably high in western and midwestern ground water aquifers. These high variations account in large measure for differential household damages.

Water quality varies enormously by geographic area. TDS levels ranging from less than 50 ppm in the South to well over 100,000 ppm in the West have been observed. Furthermore, extreme variability can even occur within the same aquifer. Near Sedgwick, Colorado, for instance, TDS and hardness were measured as 2140 and 990 ppm, respectively, in one private well but only 330 and 199 ppm in another well less than one mile away (Hurr, 1972). To obtain typical TDS or hardness values is thus meaningless for most areas of the country, especially the West and Southwest. For purposes of estimating aggregate damages, however, average values are useful inputs.

Water quality data were compiled from annual water resources reports, special state ground water reports, and information files in state agencies. Public water supply data was extracted from two USGS surveys (Durfor and Becker, 1965; Schneider, 1968) of major cities in the United States, The more recent data was selected if given the choice. Water quality observations were first separated into surface and ground sources. Then they were weighted by customers served in each municipality to yield a state average. Private well water data were more difficult to obtain. Observations were few in number and scattered in various documents. Some raw ground water records were compiled in annual surveys (U.S. Geological Survey, 1967-1970), but they covered fewer than half of all states. Other state data were taken from ground water analyses in the above mentioned USGS surveys of major cities. For another group of states, representative well samples were released by officials in USGS Water Resources District Offices. Still other information was found in special state ground water circulars. For each state a typical value of raw water quality was obtained by finding the mean of sample values. While caution must be exercised in using this as a representative value, the samples were chosen in heavily used aquifers. If water quality was found to be highly variable across the state, more than one of the above data references was used to assure better coverage.

From these data observations, water quality levels were estimated for each major supply source. In a few states, i.e., Maine and Minnesota, sample data for public ground water supplies were not readily available. A typical value was then calculated as the average of treated surface and well water quality.* By substituting water quality levels into the damage functions (Table 1), economic assessments of typical household damages from water use can he obtained.

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*Where water quality estimates for all supply sources by state are available, this averaging principle gives mixed results. For example, in Georgia and Idaho, treated ground water quality is roughly the average of values from other sources. In New York and California, this assumption yields underestimates, while the opposite occurs in Nebraska and Colorado.

SECTION VII

REGIONAL ESTIMATES OF ECONOMIC DAMAGES

A computer program was written to calculate 1970 household damages aggregated by state (including the District of Columbia). Tables 2-4 present a facsimile of the computer output. Damages are calculated for three discount rates: 5, 7.5, and 10%. In each table the first two columns estimate the annualized value (capital and operation) of all household items affected by observed (original) water quality. Next the damages are totalled over the number of households served by each supply source. Finally, these estimates are translated into per capita rankings. All damage values are based upon complete elimination of TDS and hardness prior to household use of water. This assumption results in a conservative value since household activities generally add more salts and minerals to the water supply (Bovet, 1973).

When the discount rate increases, household expenditures also rise, as expected. But the total per capita damage decreases. Intuitively, one would expect damages to change in the same ratio as expenditures. Examination of the capital recovery factor explains this discrepancy. For illustration, damages are calculated for water piping (unit 1) as affected by treated surface water in the state of Maine. With original water quality the annualized capital value increases 89% as interest goes from 5 to 10%. On the other hand, as water quality improves, this value decreases (because the service life

Table 2
HOUSEHOLD DAMAGES OF WATER SUPPLY BY STATE
FOR 1970

DISCOUNT RATE = 5%

STATE	HOUSEHLD EXPND TOTAL ($M)	HOUSEHLD EXPND PER CAPITA ($)	TOTAL DAMAGES ($1 M) BY SOURCE SURFACE	TR.GROUND	RAW WELL	TOTAL
MAINE	105.5	106.34	0.7	0.5	1.5	2.7
MASSACHUSETTS	792.6	139.32	3.7	5.3	3.8	12.8
VERMONT	51.4	115.73	0.5	0.4	0.8	1.7
NEW HAMPSHIRE	93.3	126.46	0.3	1.0	1.3	2.5
CONNECTICUT	497.4	164.05	5.8	2.9	3.5	12.2
RHODE ISLAND	121.8	128.65	1.4	0.5	0.2	2.1
NEW YORK	2753.7	150.99	39.1	61.3	15.6	115.9
NEW JERSEY	1133.7	158.16	8.9	12.9	14.7	36.5
DIST. COLUMBIA	97.9	129.39	6.3	0.0	0.3	6.6
PENNSYLVANIA	1584.6	134.36	50.2	13.0	21.0	84.2
WEST VIRGINIA	180.5	103.48	3.4	2.7	3.7	9.9
MARYLAND	583.4	148.74	13.3	1.8	2.4	17.4
VIRGINIA	588.1	126.52	11.6	2.9	11.0	25.4
DELAWARE	77.3	140.99	0.8	1.9	0.7	3.4
KENTUCKY	347.9	108.09	11.2	2.4	10.7	24.3
TENNESSEE	419.2	106.84	8.2	2.8	3.7	14.7
MISSISSIPPI	184.0	82.98	0.6	3.4	1.4	5.4
ALABAMA	350.3	101.70	6.4	3.5	3.3	13.2
GEORGIA	516.5	112.53	2.9	3.7	10.0	16.6
NORTH CAROLINA	542.6	106.77	5.2	2.4	9.8	17.3
SOUTH CAROLINA	250.0	96.51	2.0	0.4	0.6	3.0
FLORIDA	905.3	133.34	5.4	41.4	18.8	65.6
OHIO	1542.7	144.83	48.8	19.2	58.4	126.4

Table 2 (continued).

STATE	HOUSEHLD EXPND TOTAL ($M)	HOUSEHLD EXPND PER CAPITA ($)	TOTAL DAMAGES ($1 M) BY SOURCE SURFACE	TR.GROUND	RAW WELL	TOTAL
INDIANA	758.2	145.98	26.8	35.2	32.5	94.6
ILLINOIS	1750.3	157.49	51.9	62.1	57.0	171.0
MICHIGAN	1318.4	148.56	41.1	16.0	27.5	84.7
WISCONSIN	612.7	138.70	12.7	26.7	23.7	63.1
MINNESOTA	505.8	132.9-	5.8	16.1	15.4	37.3
ARKANSAS	180.5	93.86	0.7	2.3	4.9	7.9
LOUISIANA	365.4	100.35	7.2	3.8	2.6	13.6
OKLAHOMA	313.4	122.46	13.0	6.2	11.0	30.2
TEXAS	1406.2	125.59	39.5	69.2	12.4	121.0
NEW MEXICO	121.4	110.49	0.4	10.2	8.6	19.2
MISSOURI	614.3	131.36	17.7	15.4	16.2	49.4
IOWA	377.0	133.48	4.5	26.2	13.0	43.6
NEBRASKA	186.2	125.51	2.5	11.0	4.9	18.3
KANSAS	297.2	132.30	11.1	8.8	9.1	29.0
NORTH DAKOTA	69.3	112.15	1.7	2.2	3.8	7.6
SOUTH DAKOTA	77.0	115.63	0.5	3.3	7.9	11.7
MONTANA	82.1	118.25	2.4	1.3	2.4	6.1
WYOMING	43.2	129.99	1.0	1.3	1.7	3.9
UTAH	135.5	127.91	3.6	6.3	6.3	16.2
COLORADO	292.0	132.27	9.1	2.3	8.0	19.4
CALIFORNIA	3031.2	151.92	103.3	111.6	14.9	229.8
ARIZONA	250.4	141.38	9.7	21.7	8.0	39.5
NEVADA	72.7	148.64	0.6	3.4	1.1	5.1
HAWAII	107.0	139.26	0.2	3.4	1.2	4.7
WASHINGTON	469.7	137.78	3.1	9.4	2.4	14.9
OREGON	269.7	128.98	0.6	1.6	1.8	4.0
IDAHO	84.3	118.25	0.4	3.3	2.8	6.5
ALASKA	42.0	139.66	0.4	0.6	1.0	2.1

Table 2 (continued).

STATE	PER CAPITA DAMAGES ($) BY SOURCE SURFACE	TR.GROUND	RAW WELL	TOTAL
MAINE	1.16	3.41	5.60	2.69
MASSACHUSETTS	0.99	3.83	6.60	2.24
VERMONT	2.91	3.95	4.96	3.90
NEW HAMPSHIRE	1.07	3.75	6.39	3.44
CONNECTICUT	3.03	4.92	6.76	4.03
RHODE ISLAND	2.14	2.33	2.45	2.21
NEW YORK	3.19	14.80	8.53	6.36
NEW JERSEY	3.61	5.87	5.87	5.10
DIST. COLUMBIA	8.72	0.0	8.72	8.72
PENNSYLVANIA	5.75	9.22	12.70	7.14
WEST VIRGINIA	3.81	6.35	8.88	5.65
MARYLAND	4.48	4.42	4.29	4.45
VIRGINIA	4.00	6.26	8.47	5.47
DELAWARE	3.75	7.93	8.03	6.29
KENTUCKY	6.05	8.05	10.04	7.56
TENNESSEE	4.58	2.50	3.66	3.75
MISSISSIPPI	2.21	2.42	2.61	2.44
ALABAMA	3.80	3.85	3.88	3.83
GEORGIA	1.48	3.13	6.80	3.61
NORTH CAROLINA	2.41	3.39	4.37	3.41
SOUTH CAROLINA	1.18	1.15	1.09	1.16
FLORIDA	9.68	9.13	11.05	9.65
OHIO	8.53	8.10	22.84	11.87
INDIANA	12.95	22.54	20.89	18.22
ILLINOIS	9.18	19.19	25.64	15.38

Table 2 (continued).

STATE	PER CAPITA DAMAGES ($) BY SOURCE SURFACE	TR.GROUND	RAW WELL	TOTAL
MICHIGAN	7.23	11.36	15.49	9.54
WISCONSIN	8.15	17.43	17.86	14.29
MINNESOTA	4.51	10.34	16.20	9.81
ARKANSAS	1.11	3.96	6.84	4.11
LOUISIANA	4.82	2.70	3.52	3.74
OKLAHOMA	8.77	11.03	21.49	11.81
TEXAS	7.44	13.26	18.39	10.81
NEW MEXICO	5.61	16.56	25.67	18.88
MISSOURI	6.21	17.37	17.37	10.56
IOWA	7.99	15.45	22.93	15.45
NEBRASKA	11.02	11.40	16.53	12.37
KANSAS	12.33	9.81	20.21	12.90
NORTH DAKOTA	8.43	11.98	15.63	12.27
SOUTH DAKOTA	5.30	14.37	23.60	17.59
MONTANA	7.02	9.08	11.18	8.74
WYOMING	8.02	10.01	19.95	11.78
UTAH	10.40	16.23	19.26	15.28
COLORADO	5.40	7.36	36.42	8.77
CALIFORNIA	9.52	13.78	14.96	11.52
ARIZONA	20.76	23.84	20.49	22.29
NEVADA	3.48	14.09	13.49	10.47
HAWAII	6.18	6.18	6.18	6.18
WASHINGTON	1.67	8.32	5.84	4.36
OREGON	0.57	3.36	3.36	1.89
IDAHO	5.75	7.82	12.80	9.17
ALASKA	4.77	7.73	7.73	6.91